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Quantitative analysis of thermal insulation coatings

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Abstract

This work concerns the development of simulation tools for mapping of insulation properties of thermal insulation coatings based on selected functional filler materials. A mathematical model, which includes the underlying physics (i.e. thermal conductivity of a heterogeneous two-component coating and porosity and thermal conductivity of selected fillers) was recently developed. The model has been validated against data from a previous experimental investigation with hollow glass sphere-based epoxy and acrylic coatings. In this presentation, a concise introduction to the model and some of the simulation results are provided. A practical case story with an insulation coating applied to a hot water pipe is included. Further development of the simulation tool to other types of fillers will be shortly discussed.

Introduction

Thermal insulation coatings basically consist of a binder with a functional filler material dispersed in the matrix. The filler is made in such a way that it contains “still” air and thereby has a low thermal conductivity, providing insulation properties to the coating. Hollow glass and ceramic spheres are examples of functional fillers, but also silica aerogels are used [1,2].

Traditionally, processing equipment and piping have been insulated with mineral wool or polyurethane foam, but layers of insulation can often hide severe maintenance problems such as corrosion under insulation (CUI) [1]. In crude terms, corrosion occurs when the steel surface below the insulation layer comes into contact with water containing ions from dissolved impurities [3]. Often, the steel surface is coated, but CUI can still take place, where coating failures are present (or develop). An alternative way to insulation properties is the use of thermal insulation coatings, which are applied in thicknesses of a few millimeters. These coatings cannot provide the same level of insulation as traditional methods, but is certianly better than having no insulation and maintenance costs are typically lower. An important added benefit is greater ease of application, in particular for complex geometries. Furthermore, industrial workers must often be protected against burns from contact with hot surfaces (so-called “safe-touch” properties) and here thermal insulation coatings can help reducing the surface temperature and the rate of thermal energy transfer from equipment and piping [1]. Several commercial insulation coatings are on the market and can be applied directly to the substrate or over an anticorrosive primer with a subsequent top coating for decorative properties and protection of the insulation coating [1].

Hollow glass spheres are made from sodium or aluminium borosilicate glass and contain a small amount of air. The thermal conductivity of an aerogel is very low, but according to Achar and Procopio [1], binder intrusion into the open cell pore structure may take place during coating formulation and application and displace some of the air. On the other hand, Pidhurney and Pescatore [2] state that high shear forces during mixing and spraying of a coating may break hollow glass spheres. Therefore, the choice of functional filler material will depend on the specific application and a variety of aerogel surface treatments and hollow glass sphere diameters and wall thicknesses are available. Other materials, such as polymer microspheres [4], are also used. Despite the incipient commercial success of thermal insulation coatings as non-specialized coatings, very few scientific reports on the mechanisms and optimization of thermal insulation coatings have been published [5].

In this work, a mathematical model, which quantifies the behavior of a thermal insulation coating based on hollow spheres, is considered and some results discussed. Simulations of interest include the effects of sphere wall thickness, pigment (hollow sphere) volume concentration (PVC), thermal conductivities of binder and wall materials, and filler size distribution.

Mathematical model of insulation coating

The mathematical model was presented and verified against experimental data for epoxy and acrylic coatings in a recent publication [5] and here will only be given a very concise, equation-free introduction. The model is capable of estimating the thermal conductivity of a thermal insulation coating based on hollow spheres. The coating structure is schematically shown in Fig. 1. The model takes into account the sphere wall thickness, the sphere wall material, the porosity of the hollow spheres, the pigment (hollow sphere) volume concentration (PVC) in the coating, and the type of binder matrix material used. In [5], an analysis of a case story with an insulation coating applied to a hot water pipe is also included.

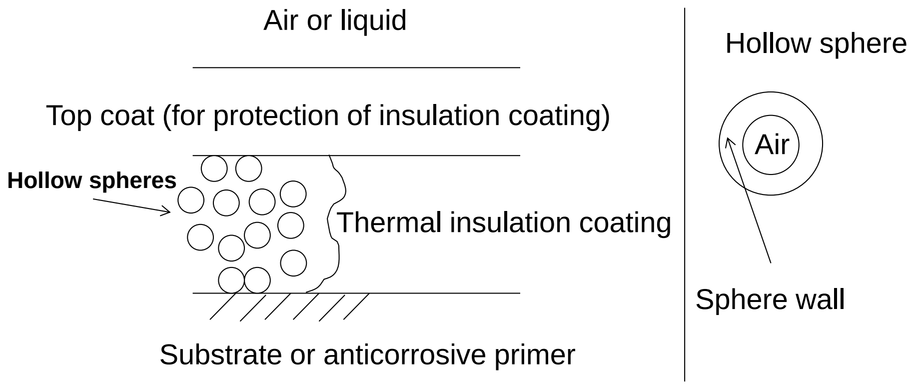

Figure 1: Schematic illustration (cross-section view) of a thermal insulation coating based on hollow spheres (left). On the right, a single hollow sphere is shown. After [5].

Results and Discussion

The present version of the model is capable of estimating the effect of hollow spheres on the thermal conductivity of an insulation coating. As an example, in this short communication, the effect of pigment (hollow sphere) volume concentration (PVC) on the thermal conductivity of the coating is considered. This parameter is of significant importance for the coating formulator. Values of PVC above the critical pigment volume concentration (CPVC) should be avoided because many coating properties are compromised at this point. The coating becomes porous (in the binder matrix) above CPVC and this may be tempting to exploit for insulation purposes, but mechanical properties in particular are suffering under such conditions.

The effect of PVC on the thermal conductivity of a coating is shown in Fig. 2. The y-axis co-ordinate, $k_C/k_B°$, is the ratio of the thermal conductivity of the coating to that of the binder alone (i.e. a filler-free coating). The independent variable on the x-axis is the ratio of the sphere wall thickness, δ, to the volume-average diameter of a hollow sphere, d_{po}. It can be seen that for $k_C/k_B°<1$, the higher the PVC, the better the insulation properties. The opposite is found for $k_C/k_B°>1$. The reason for this is that the effect of the added wall material (which has a high thermal conductivity), at some point, becomes more important than the effect of additional air. Therefore, optimal thermal properties are, theoretically, obtained with as small a wall thickness as possible and a PVC as close to the CPVC as possible. However, it must be kept in mind that the mechanical stability of the spheres is lowered when sphere wall thickness is reduced and that formulation close to the CPVC value is risky because coating properties change dramatically if PVC exceeds CPVC. More details are available in [5].

Conclusions

The mathematical model developed in [5] is able to simulate experimental data available for selected insulation coatings. The phenomena influencing the rate of thermal conductivity of the coating have been mapped. In the presentation, a range of simulations with the model will be shown and discussed. Future work with the model involves extension to other types of filler materials with insulation properties (e.g. silica aerogels).

Acknowledgement

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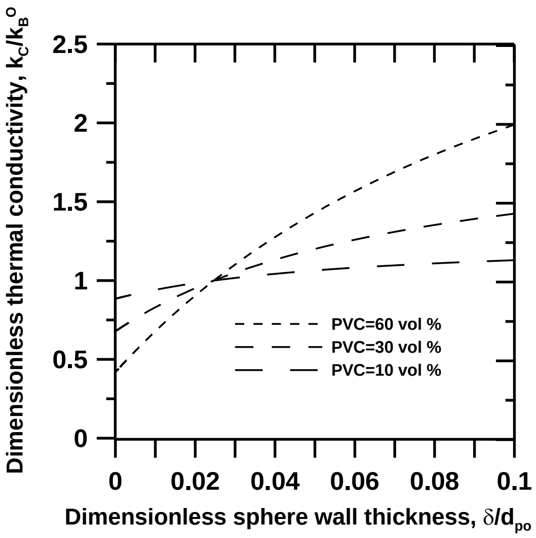

Figure 2: Simulations of the effect of the pigment (hollow glass sphere) volume concentration, PVC, on the dimensionless thermal conductivity of the thermal insulation coating, k_C/k_B^o. The independent variable, δ/d_{po}, is the ratio of the wall thickness and diameter of the hollow glass spheres. Parameters are: d_{po}=40 μm, T=25 ℃ , k_B^o=183 mW/(m·K) (thermal conductivity of epoxy binder), and k_G=1140 mW/(m·K) (thermal conductivity of borosilicate glass). After [5].

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